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The dynamics of slug trains in volcanic conduits: Evidence for expansion driven slug coalescence

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ABSTRACT

Strombolian volcanism is a ubiquitous form of activity, driven by the ascent and bursting of bubbles of slug morphology. Whilst considerable attention has been devoted to understanding the behaviour of individual slugs in this regime, relatively little is known about how inter-slug interactions modify flow conditions. Recently, we reported on high temporal frequency strombolian activity on Etna, in which the larger erupted slug masses were followed by longer intervals before the following explosion than the smaller bursts (Pering et al., 2015). We hypothesised that this behaviour arose from the coalescence of ascending slugs causing a prolonged lag before arrival of the next distinct bubble. Here we consider the potential importance of inter-slug interactions for the dynamics of strombolian volcanism, by reporting on the first study into the behaviour of trains of ascending gas slugs, scaled to the expansion rates in volcanic conduits. This laboratory analogue study illustrates that slugs in trains rise faster than individual slugs, and can be associated with aspects of co-current flow. The work also highlights that coalescence and inter-slug interactions play an important role in modulating slug train behaviour. We also report, for the first time, on slug coalescence driven by vertical expansion of the trailing slug, a process which can occur, even where the leading slug base ascent velocity is greater than that of the trailing slug.

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1. Introduction

Strombolian activity is a highly ubiquitous form of volcanism, driven by the ascent and bursting of gas slugs, i.e., bubbles of width approaching that of the magma conduit and of length greater than or equal to this width. Whilst there has been considerable focus on the behaviour of single slug volcanic regimes (e.g., Seyfried and Freundt, 2000; James et al., 2008, 2009; Ozerov, 2010; Suckale et al., 2010, 2011; Del Bello et al., 2012, 2015; Lane et al., 2013; Vergnolle and Gaudemer, 2015; Capponi et al., 2016 and references therein), very little attention has been devoted to the dynamics of multiple slug behaviour (e.g., Seyfried and Freundt, 2000; James et al., 2004; Llewellyn et al., 2013, 2014). A number of volcanoes exhibit strombolian activity, which varies in temporal frequency and explosive strength between targets. Key examples include: Yasur, where explosions occur on timescales of minutes (Kremers et al., 2013; Marchetti et al., 2013; Spina et al., 2016); Stromboli, the archetypal

location for this activity, characterised by explosions every 5–10 minutes (Ripepe and Marchetti, 2002; Ripepe et al., 2002); Mt. Erebus, which exhibits sporadic strombolian explosions (Rowe et al., 1998); Shishaldin, which experienced strombolian phases in 1999 with explosions frequencies of 0.7–1.5 Hz (Vergnolle et al., 2004); and Etna, which produces strombolian eruptions, with inter-event spacings ranging from seconds to hours, during eruptive activity (Vergnolle and Ripepe, 2008). In contrast to the aforementioned violent strombolian explosions which are associated with the ejection of ash and/or incandescent pyroclastic material and occur on timescales of minutes to hours, in-conduit slug flow can also be associated with ‘puffing’. Puffing is characterised by an acceleration of gas emissions at the surface, associated with the burst of gas slugs or spherical-cap bubbles, but lacks the explosive aspect of a strombolian explosion (James et al., 2009; Tamburello et al., 2012), and can occur on timescales of seconds, e.g., as at Stromboli (Gaudin et al., 2017) and Erta Ale, which exhibits bursting trains of spherical-cap bubbles (Bouche et al., 2010).

Recently, we reported on rapid strombolian activity (with an event frequency of ≈ 0.25 Hz) on Mt. Etna, in which we noted that the largest erupted gas masses were followed by the longest return periods before

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the following explosion (Pering et al., 2015). We termed this phenomenon the ‘repose gap’, hypothesising that it originated from the coalescence of closely spaced slugs in the conduit, forming larger slugs, which were followed by prolonged delays before arrival of the next slug at the surface. This raises a question regarding the extent to which coalescence could modulate the magnitude and timing of strombolian explosions during such rapid multiple-slug activity, by altering the distribution of slug gas masses within the conduit. In order to further consider the role of coalescence, we report here on the first experimental study into the behaviour of rising trains of interacting slugs in a vertical conduit, where expansion rates have been scaled to the volcanic scenario, which previous coalescence studies (Mayor et al., 2008b; Santos et al., 2008; Santos and Coelho Pinheiro, 2014) have not considered. We refer to the continuous slug flow investigated here as ‘slug train’ flow, preferring this nomenclature to ‘multiple slugs’.

During ascent of a single slug in a volcanic conduit, a static pressure drop leads to slug expansion before eventual burst at the surface (James et al., 2008; Santos et al., 2008; Santos and Coelho Pinheiro, 2014). Interactions between ascending slugs can begin to occur when two or more slugs are contained within a conduit, such that important controls include: the bubble separation distance, conduit dimensions, liquid rheology, and liquid velocity. In particular, the liquid velocity scenarios can be termed as stagnant or co-current, i.e., in the latter case where a liquid has an upward velocity (Morgado et al., 2016). Liquid velocity is important as it affects the ascent velocity and expansion rate of a slug, which has implications for the slug interaction dynamics (Nicklin et al., 1962; Pinto et al., 1998, 2001, 2005).

The study of interactions between rising slugs has been largely limited to slug pairs in stagnant and co-current liquids. Observations have provided constraints on the fluid dynamic behaviour and the minimum inter-slug distances, at which slugs ascend independently of one another (Pinto and Campos, 1996; Pinto et al., 1998, 2001; Araújo et al., 2013, 2015). However, during sustained rapid strombolian activity, such as that observed on Etna (Pering et al., 2015), the behaviour of trains of ascending slugs becomes much more important (Taitel et al., 1980; Joseph et al., 1996; Mayor et al., 2008a, 2008b; Xia et al., 2009). During slug train scenarios, at the non-volcanic scale, slug expansion has been demonstrated to be a key process (Santos et al., 2008; Santos and Coelho Pinheiro, 2014). Mayor et al. (2008b) considered interacting slugs in a slug train scenario including expansion but for far lower expansion rates than at the volcanic scale, as considered in our study. In particular, they demonstrated that slug expansion only played a limited role in expediting coalescence in that non-volcanic scale case. Interaction between slugs in a slug train scenario also depends on the stability and transition of slugs between different morphologies, i.e., from bubbly to slug and then churn flow (e.g., Taitel et al., 1980; Joseph et al., 1996). The study of slug trains in vertical conduits can also reveal statistical information regarding the slug flow parameters, e.g., bubble length and separation distances which are important for understanding slug-slug interactions (Tsuchiya and Nakanishi, 1992; Mayor et al., 2008a; Xia et al., 2009). Before reporting on our experiments into the dynamics of slug train behaviour, including the associated slug interaction and coalescence, we first detail the physics of individual slug flow in conduits.

2. Slug theory and coalescence

A single slug (see Fig. 1) within a conduit has a constant slug base ascent velocity, U_{sl} (Wallis, 1969; Viana et al., 2003), whilst the slug nose accelerates towards the surface due to decompressional expansion (James et al., 2008). Henceforth, we assume a cylindrical conduit, constant viscosity, and laminar flow for the calculation of the following aspects of slug flow. The ascent velocity of the base of the slug is defined by:

$$U_{sl} = Fr \sqrt{2gr_c} \quad (1)$$

where g is gravitational acceleration, r_c is the conduit radius, the Froude

number, Fr is determined following Llewellyn et al. (2012):

$$Fr = 0.34 \left[1 + \left(\frac{31.08}{N_f} \right)^{1.45} \right]^{-0.71} \quad (2)$$

and the dimensionless inverse viscosity, N_f is defined by:

$$N_f = \frac{\rho_m}{\mu} \sqrt{g(2r_c)^3} \quad (3)$$

such that ρ_m is the magma density and μ , the magma viscosity. Llewellyn et al. (2012) then use N_f to estimate the thickness of the falling film (λ') which separates the slug from the conduit wall:

$$\lambda' = 0.204 + 0.123 \tanh(2.66 - 1.15 \log_{10} N_f) \quad (4)$$

Llewellyn et al. (2012) is used as it is applicable to regimes where interfacial-tension between the liquid and gas phase can be neglected, such that λ' can be obtained directly using N_f .

An ascending slug has a trailing wake, a feature which can range characteristically, from being open and turbulent, to closed and axisymmetric (Campos and Guedes de Carvalho, 1988; Nogueira et al., 2006a). The wake is followed by a ‘wake interaction length’, which is typically four times as long as the wake itself, and defines an area of fluid disturbance which will influence trailing bubbles, potentially causing coalescence. The wake length (l_{wake}) and wake interaction length (l_{min}) are characterised below, with formulations that are valid for laminar and closed axisymmetric wakes relevant to the volcanic scenario. Firstly, according to Campos and Guedes de Carvalho (1988):

$$l_{wake} = 2r_c (0.30 + 1.22 \times 10^{-3} N_f) \quad (5)$$

and, secondly, as per Pinto and Campos (1996):

$$l_{min} = 2r_c (1.46 + 4.75 \times 10^{-3} N_f) \quad (6)$$

Here, we have used N_f to estimate the existence and dimensions of a slug wake and interaction length. However, others have used the Reynolds number (for more detail and discussion see Vergnolle and Ripepe, 2008; Bouche et al., 2010; Suckale et al., 2010, 2011; James et al., 2011; Vergnolle and Gaudemer, 2015) to describe the characteristics of gas slug ascent and wake behaviour.

The coalescence of two ascending slugs begins when the trailing slug enters the wake interaction length of the leading slug, at which point the entire trailing slug accelerates upwards. On entering the wake, the trailing slug is further accelerated, aided by the non-static liquid in the wake, which can be pulled down into the trailing slug’s falling film, ultimately leading to coalescence and formation of a single larger slug (Pinto and Campos, 1996; Araújo et al., 2013).

Where more than two slugs rise through a liquid, the dynamics become considerably more complex, particularly if gas expansion is important (Mayor et al., 2008a, 2008b). Expanding slugs induce an upward velocity on the overlying fluid, such that this liquid’s velocity is driven by the expanding slug’s length (Santos et al., 2008; Santos and Coelho Pinheiro, 2014). Any slug above this fluid will therefore also be affected by this expansion, prompting acceleration of such slugs, a process which will be additive in a slug train, such that each slug’s velocity is driven by the cumulative effect of the expansion of all trailing slugs in the conduit (Mayor et al., 2008a, 2008b). In this scenario, the increase in slug velocity will be, to a degree, dependent on inter-slug spacing and slug length, i.e., the velocity field created in the fluid above each slug will have a stronger effect on overlying slugs at smaller inter-slug spacings and will also be expedited for longer slugs which undergo more expansion (Pinto et al., 1998, 2001). Overall, this leads to the development of a flow with co-current like characteristics, where the liquid

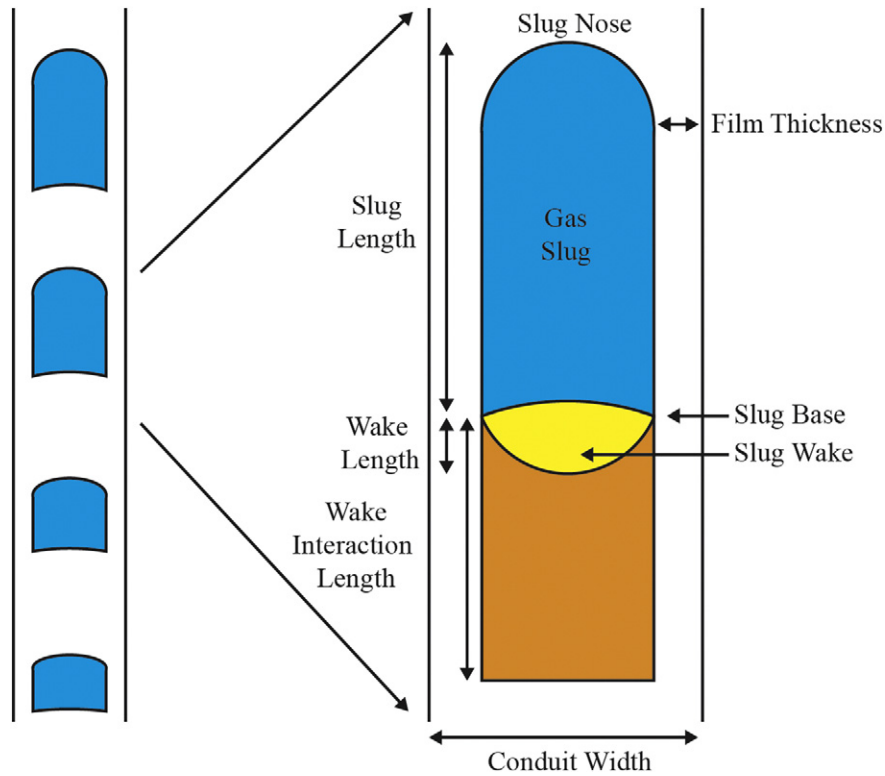


Fig. 1. (Left) an illustration of a slug train and (right) important features of a gas slug.

will be locally non-stagnant, with non-constant velocity, and potential implications for the coalescence process. The rise speed of a slug in a co-current flow regime U_{csl} relates to U_{sl} and the liquid velocity, U_l via the following relation (Nicklin et al., 1962; Santos et al., 2008):

$$U_{csl} = U_{sl} + C U_l \quad (7)$$

where C is a constant between 0.13 and 0.4.

3. Experimental setup and scaling

In order to investigate the behaviour of rising slug trains, twelve laboratory experiments were conducted (Lab 1–Lab 12) to probe a range of volcanically scaled regimes. The experiments were performed using a similar set-up to Lane et al. (2013) and Del Bello et al. (2015). A bubble injector was installed at the base of a borosilicate glass tube of ≈ 1.8 m length and ≈ 0.025 m width, filled to a depth of ≈ 1 m with mechanical vacuum pump oil of density and viscosity values of 862 ± 2 kg m $^{-3}$ and 0.162 ± 0.004 Pa s, respectively. A flow rate meter was used to monitor the average gas flow rate, which was set to ≈ 9 , ≈ 50 , or ≈ 175 cm 3 s $^{-1}$ during each experiment, producing bubbles of morphology ranging from spherical-cap bubbles to slugs on injection. A vacuum pump was connected to the top of the tube to provide constant surface pressure values of ≈ 0.5 , 1, 3 or 5 kPa, giving twelve permutations of the experimental conditions (Table 1) with distinct column integrated gas volume fractions.

The laboratory experiments are scaled to mimic low viscosity Newtonian magmatic processes within a vertical cylindrical conduit at basaltic volcanoes. Our experimental fluid and tube properties give an N_f value of ≈ 66 (using Eq. (3)), which is appropriately scaled for a volcanic scenario (Del Bello et al., 2012; Lane et al., 2013) for the case of slugs with closed axisymmetric wakes. The experimental scaling for slug expansion is an important consideration, given the potential role of this process in slug coalescence, with our experimental pressures leading to scaling for slug expansion over a broad range of conduit lengths, i.e., ≈ 200 – 2000 m

(Lane et al., 2013). For a full and complete description of the scaling associated with these experiments please see the Supplementary material (S1) of Lane et al., 2013, which contains a detailed breakdown of scaling for an identical experimental setup to our own, but different applied surface pressures.

The most important aspect of scaling for our experiments is the time available for the coalescence process to happen, which links to distance over which this will occur. The coalescence of two slugs within the experiments took ≈ 3 s. For a minimum slug base velocity, calculated using Viana et al. (2003), of ≈ 0.14 m s $^{-1}$, this corresponds to coalescence occurring over a distance of ≈ 0.42 m. The coalescence process would therefore scale using the ratio of this coalescence distance to l_{min} , which is ≈ 9.5 (using an N_f of 66), with l_{min} dependent on N_f as detailed in Eq. (6). We can therefore estimate the distance needed for coalescence in a volcanic scenario. For example, a basaltic magma of density ≈ 2600 kg m $^{-3}$ and viscosity ≈ 500 Pa s, within a conduit

Table 1

Parameters for each laboratory experiment, including calculated average slug lengths, gas volume fractions (GVF), number of slugs which coalesce per second, the number of slugs observed to enter the tube base from the DSLR imagery, and the R^2 values for linear trends indicated in Fig. 3c.

	Av. flow rate (cm 3 s $^{-1}$)	Pressure (kPa)	Av. slug length (mm)	Av. GVF (%)	Coalescence rate (s $^{-1}$)	Total slugs	R^2
Lab 1	9	1	17	8	0.33	598	0.59
Lab 2	50	1	50	27	0.57	713	0.78
Lab 3	175	1	209	58	0.51	555	0.88
Lab 4	9	0.5	24	9	0.32	542	0.73
Lab 5	50	0.5	57	29	0.68	489	0.84
Lab 6	175	0.5	224	63	0.54	348	0.76
Lab 7	9	3	10	6	0.35	251	0.62
Lab 8	50	3	27	18	0.59	815	0.82
Lab 9	175	3	116	50	0.62	506	0.95
Lab 10	9	5	8	7	0.31	337	0.65
Lab 11	50	5	18	16	0.60	452	0.69
Lab 12	175	5	74	40	0.61	371	0.60

diameter ≈ 3 m, would have an associated $l_{\min} \approx 5.59$ m. This, in turn, using the above ratio gives an approximate distance needed for coalescence to occur of ≈ 53 m. In the laboratory case and a volcanic case (for a 200 m long conduit) the ratio of conduit length to coalescence distance is ≈ 4 , demonstrating the suitability of this scaling to enable capture of the coalescence process.

Each laboratory experiment was recorded using a 300 fps (frames per second) Basler A602f camera (e.g., see Lane et al., 2013; Capponi et al., 2016). Example imagery is shown in Fig. 2 for a number of the experimental runs. The slug base and nose positions were tracked manually using ImageJ® and plugin MTrackj (<http://www.imagejscience.org/migering/software/mtrackj/>) software in order to investigate coalescence activity. In particular, the following parameters were extracted for pairs of adjacent slugs: the trailing and leading slug base ascent velocities, both slug lengths, the gap length (i.e., the distance between the trailing slug nose and the leading slug base), and the gap length plus trailing slug length. This final parameter can be used to determine when wholesale interaction between the slugs occurs, i.e., a decrease in this length indicates that the whole of the trailing slug is accelerating towards the base of the leading slug, which would occur if only two slugs were in the conduit. Any departure from this would indicate a change in coalescence mechanism. The gap length also shortens in the event of coalescence, and is furthermore affected by any lengthening of the trailing slug.

A DSLR (digital single-lens reflex) camera was also used to capture video at 25 fps to enable constraints on bulk features of each experimental configuration, and to count the number and position of coalescence events. Gas volume fraction was calculated by taking DSLR images and extracting average ratios of gas to liquid volume through time (i.e., taking into account falling film, in addition to the liquid separating quasi-cylindrical slugs).

4. Bulk slug train dynamics

The DSLR footage enabled the analysis of >5900 bubbles, including investigation of the whole-column bulk slug behaviour. Experimental bulk data are shown in Fig. 3, for each of our experimental configurations, in particular the average slug base ascent velocity (i.e., time-averaged between the appearance of the bubble at the tube base, to its arrival at the surface) and slug length on arrival at the surface, for non-coalescing slugs (i.e., velocities of coalescing slugs are affected by the coalescence process), were plotted against gas volume fraction for each experiment (Fig. 3a and b, respectively). Fig. 3a shows that the slug base ascent velocity increases in a quasi-linear manner, above the theoretical value for the single slug regime (Viana et al., 2003) as gas volume fraction increases beyond $\approx 30\%$, likely driven by larger volume expanding slugs which generate the additive increase in velocity detailed above. Significant viscosity effects may be added in addition, given the high proportion of liquid in the surrounding film.

Fig. 3c shows plots of repose time (i.e., the lag until the following bubble arrives at the surface) per burst vs. the bursting slug's length for a number of events from each experiment, showing linear trends and a decreasing gradient with increasing gas volume fraction. In addition, Fig. 3c shows that with increasing slug length the minimum observed repose time increases, a direct observation of 'repose gap' behaviour (Pering et al., 2015). See Appendix A for further details and the raw data used to generate Fig. 3.

Fig. 4 shows bulk slug train characteristics associated with bubble coalescence from each of the experiments. In particular, a number of parameters are plotted against gas volume fraction in each case: a) the coalescence rate (the number of coalescence events occurring per second); b) coalescence position (taken as the mean position where the trailing slug nose and leading slug base meet), normalised by the height of fluid in the column; and c) normalised coalescence positions in a box and whisker plots, showing the statistical spread of this parameter, for each of the observed coalescence events. Fig. 4a reveals lower

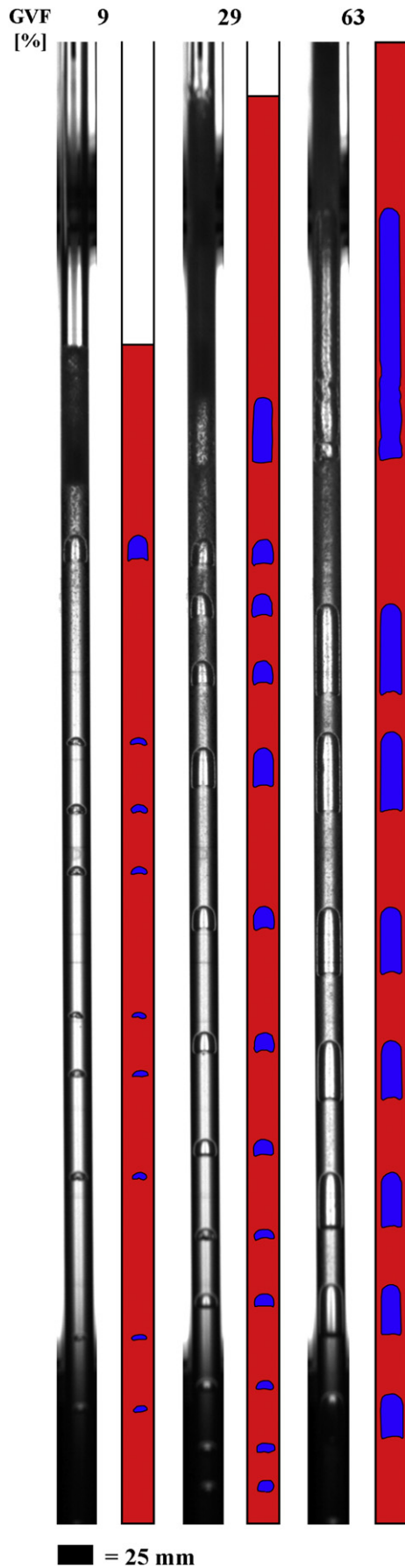
coalescence rates ($\approx 0.3\text{--}0.35\text{ s}^{-1}$) at the lowest gas volume fractions ($<10\%$), whilst the highest coalescence rates ($\approx 0.57\text{--}0.68\text{ s}^{-1}$) are associated with gas volume fraction values $\approx 15\text{--}50\%$, and mid-range coalescence rates ($\approx 0.52\text{--}0.54\text{ s}^{-1}$) are linked to gas volume fractions $\approx 58\text{--}63\%$. The latter points are associated with the highest expansion rates. Fig. 4b shows a general trend ($R^2 = 0.39$ with $P = 0.03$, and Pearson's $R = -0.63$) between mean coalescence position and gas volume fraction. Fig. 4c illustrates that, on the whole, the lower quartile, mean, and median coalescence positions for each of the gas volume fraction >40% experiments are smaller than those in the lower gas volume fraction cases, further evidencing a downward migration in coalescence position with increasing gas volume fraction. Overall these data suggest that, as gas volume fraction (and hence slug length) increases, slug coalescence occurs nearer to the base of the tube, i.e., expansion has a greater effect at higher gas volume fraction, whereas at low gas volume fraction, slugs remain independent for longer in the conduit. The characteristics of individual coalescence events across the range of gas volume fractions are now discussed.

5. Slug coalescence

In total 28 coalescence events were captured in the high frequency imagery across the different experimental runs, with an example shown in Fig. 5, representing the key stages in the coalescence process: 1) the initial inter-slug interaction and acceleration of the trailing slug within the wake interaction length of the leading slug; 2) deformation of the trailing slug nose; and 3) the ultimate capture of the trailing slug, i.e., coalescence. In Fig. 6 we present coalescence data, concerning a number of events, capturing the distinct observed behaviours; for tracks of the remaining coalescence events, please see Appendix B (Figs. S1 and S2). Whilst the gas volume fraction values are column integrated, and there will be a degree of local variation in gas fraction over the column, i.e., a systematic decrease with column depth, there was nonetheless a clear evolution in the characteristics of the coalescence process, with increasing experimental gas volume fraction, as described below. In the lab, the calculated gas volume fraction values are a combination of observations of the slugs and liquid alone; whereas in a volcanic setting the gas volume fraction will also be affected by smaller bubbles, which would alter the Newtonian behaviour of the magma. In general, we observed three different styles of coalescence behaviour, which will now be identified and described in turn.

Firstly, for gas volume fraction values of up to $\approx 30\%$ (Fig. 6a and b), the pre-coalescence behaviour typically follows that of the single slug flow regime, i.e., with bubble base ascent velocities defined by Viana et al. (2003), due to the relatively large inter-slug spacing at the base of the tube. In this case, coalescence occurs as expected within a stagnant liquid containing a slug pair (Pinto and Campos, 1996; Araújo et al., 2013); the gap plus trailing length and the gap length decrease gradually for 2–3 s, until an additional acceleration of the trailing slug takes place 0.2–0.3 s before capture. The latter acceleration occurs in tandem with elongation of the trailing slug nose (i.e., indicating a non-static liquid above the trailing slug), an increase in the trailing slug length, and takes place roughly when the trailing slug enters the wake of the leading bubble. There was no change to the trailing slug base morphology throughout the coalescence process, until after capture where an inertial rebound occurs (e.g., Fig. 5 at 0.26 s). Overall, in this regime, there is more chance of coalescence where the trailing slug has a higher volume. Note also that for these lowest gas volume fraction experiments some slugs initially had spherical-cap morphologies, before transitioning into slugs through volumetric increase during ascent.

Fig. 6c–f represent coalescence events for >30% gas volume fraction conditions. Here, we observe a general trend away from single slug behaviour with increasing gas volume fraction, due to the shorter inter-slug distances at initiation. For instance, Fig. 6c and d represent a moderate gas volume fraction scenario (40%), where the slug base ascent velocities are above those expected in the single slug regime (e.g., Viana et al.,



2003), i.e., there is an increase in the velocity of the liquid in the column, facilitated by the movement of liquid in the slug wakes, through the falling films of overlying slugs. In Fig. 6c, the coalescence process otherwise occurs as would be expected in the single slug case. In contrast, in Fig. 6d, the gap plus trailing length increases prior to coalescence, as the leading slug base is travelling faster than the trailing slug base, a feature which becomes more apparent with increasing gas volume fraction. This is demonstrated in Table 2, where velocity data for the coalescence events are detailed, highlighting that in such cases, this disparity between base speeds is actually accentuated in the 1 s window, immediately prior to capture. This shows a clear departure from coalescence behaviour in the single slug regime, i.e., where the entire trailing slug is accelerated into the leading slug base (Pinto and Campos, 1996). Imagery from one such coalescence event is shown in Fig. 5, demonstrating that the shape of the trailing slug nose is preserved until this slug enters the wake area of the leading slug. We therefore propose that volumetric expansion, rather than a change in the morphology of the trailing slug nose is the key driver of coalescence in this case (Dumitrescu, 1943; Nogueira et al., 2006b), providing the first experimental observation of this behaviour.

Table 4 also shows estimates of liquid velocity from Eq. (6), using a C value of 0.2 (Santos et al., 2008), intimating the development of a co-current like flow regime for the $>30\%$ gas volume fraction runs with liquid velocities increasing with gas volume fraction, driven by the liquid surrounding and above the leading slugs being accelerated upwards (e.g., Mayor et al., 2008b), in contrast to the quasi-stagnant liquid for the smaller gas fraction experiments. Fig. 6e and f show examples of coalescence for the largest gas volume fraction experimental conditions ($>55\%$ gas volume fraction), again with coalescence being driven by expansion of the trailing slug. There are, in addition, large temporal fluctuations in the ascent velocities of all slugs in the column, due to drainage of fluid down the tube walls following burst events, or a resonant bounding of the experimental apparatus, causing significant disturbances in the underlying slug flow (see Supplementary Video 1). During the largest gas volume fraction experiments, the slugs also remained intact during passage through a foam layer, which developed at the fluid surface in all of the simulations.

5.1. The mechanism for expansion-driven slug coalescence

A single expanding slug has a base velocity, which is controlled by the flux of liquid in the falling film (Wallis, 1969; Batchelor, 1967; Viana et al., 2003), which also gives the slug nose a higher velocity. The liquid above this slug will then be accelerated upwards as the slug nose accelerates during decompression. With additional slugs in a tube, as in our slug train scenario, any slug above an expanding slug will behave as a slug within a co-current flow. Such slugs will therefore have velocities which are greater than the single slug ascent velocity (see Eq. (7)). To escape any trailing slug, the leading slug base would therefore have to ascend at a velocity of $>U_l + U_{sl}$, which is the ascent velocity according to Viana et al. (2003) plus the liquid flow velocity. However, given that the slug ascent velocity in a co-current flow, U_{csl} , is less than $U_l + U_{sl}$, as we know the constant C used in Eq. (7) to be between 0.13 and 0.4, any ascending leading slug would therefore be unable to rise quickly enough to escape the expansion of a trailing slug. Thus, the expansion of the trailing slug will drive the coalescence process, even when the trailing slug ascends with a constant base velocity, assuming it is unaffected by trailing slugs. This explains the observation of an increasing gap plus trailing length between two coalescing slugs prior to

Fig. 2. Example imagery from three laboratory experiments (Lab 4, 5 and 6) with adjacent coloured sketches to enable ready visual assessment of the bubble positions, morphologies and dimensions. The vertical extent of these illustrations is ~1.5 m.

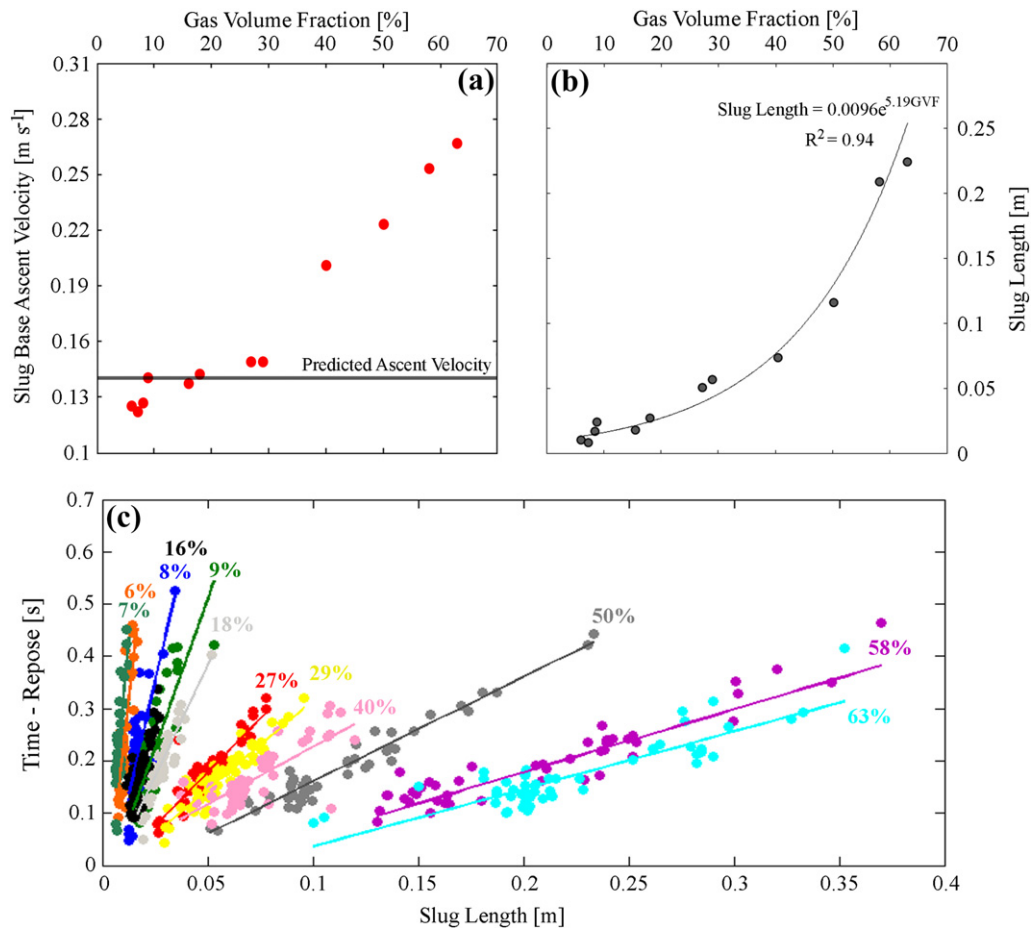


Fig. 3. The bulk behaviour of slugs in each of the laboratory experiments, in particular, showing: a) slug base ascent velocity vs. gas volume fraction, b) slug length vs. gas volume fraction; and c) repose periods following the bursts vs. slug length, with experimental gas volume fraction values indicated. Regression lines have also been added, for R^2 values see Table 1. Where the speeds in a) are below the theoretical single slug value, i.e. <10% gas volume fraction, there is a significant proportion of non-conduit filling cap bubbles.

coalescence in the slug train case, and could also explain the presence of the systematic trends between repose time and slug length in Fig. 3c.

At this stage, no further predictions or more detailed models can be produced to describe slug train behaviour (i.e., that displayed in Fig. 3) without significant further study over a broader range of scaled N_F volcanic scenarios in the laboratory and/or using computational fluid dynamics. In addition, pressure conditions and inter-slug velocities are so variable within a slug train scenario that modeling expected behaviour is problematic, especially when relying on single models for high expansion rate scenarios (e.g., James et al., 2008).

Our observations, overall, suggest that in a volcanic environment, where expansion clearly dominates in the upper portions of the conduit, such expansion-driven slug coalescence would be present. The assertion by Pering et al. (2015) that coalescence could drive 'repose gap' behaviour, whereby larger slugs are followed by longer wait periods before another burst, is entirely consistent with these experimental observations. Indeed, Gaudin et al. (2017) have also recently observed similar behaviour, which could indicate bubble coalescence, over similar inter-event intervals, at Stromboli.

6. Discussion and conclusions

Here, we report on the first study into the behaviour of trains of ascending gas slugs, scaled to the expansion rates in volcanic conduits, to investigate the fluid dynamic regime thought to drive high temporal frequency strombolian explosions. Indeed, rather different behaviour is observed when slugs are closely spaced and can interact with one another, rather than ascending independently. In particular, in the slug train

scenario, we observed non-negligible liquid velocities leading to co-current flow like behaviour and greater slug ascent velocities, than associated with single slug flow. In contrast to prior studies (e.g., Pinto et al., 1998; Mayor et al., 2008b), this work used expansion rates scaled to volcanic systems, highlighting that near-surface expansion is a key driver of coalescence in this case. Indeed, slug expansion enabled coalescence, even when the leading slug had a greater base ascent velocity than that of the trailing slug, affirming the suggestion of Mayor et al. (2008b) that inter-bubble interaction could be possible in such slug train scenarios. The observed expansion driven coalescence can be explained via two mechanisms: (1) volumetric expansion of the trailing slug during ascent as a result of a reduction in pressure; (2) when the trailing slug enters the influence of the leading slug's wake interaction length, it may be affected by the lower pressure of the leading slug, promoting expansion. Taken in tandem, these effects cause the leading slug to be unable to reach a velocity above that of the trailing slug nose, leading to expansion driven coalescence. This work also identifies the important role that coalescence played in modulating the timing and magnitude of bursting events in vertical slug train flow, for a wide variety of experimental gas volume fraction conditions (e.g., Taitel et al., 1980; Mayor et al., 2008b), notwithstanding significant variation in coalescence characteristics as a function of gas volume fraction.

This study furthermore presents intriguing laboratory derived qualitative relationships between gas volume fraction, slug base ascent velocities and slug length, in particular with slug length increasing exponentially with gas volume fraction, likely as a result of the increase in interactions between ascending slugs and falling films as slugs lengthen. In addition, slug base ascent velocities scaled in an apparently

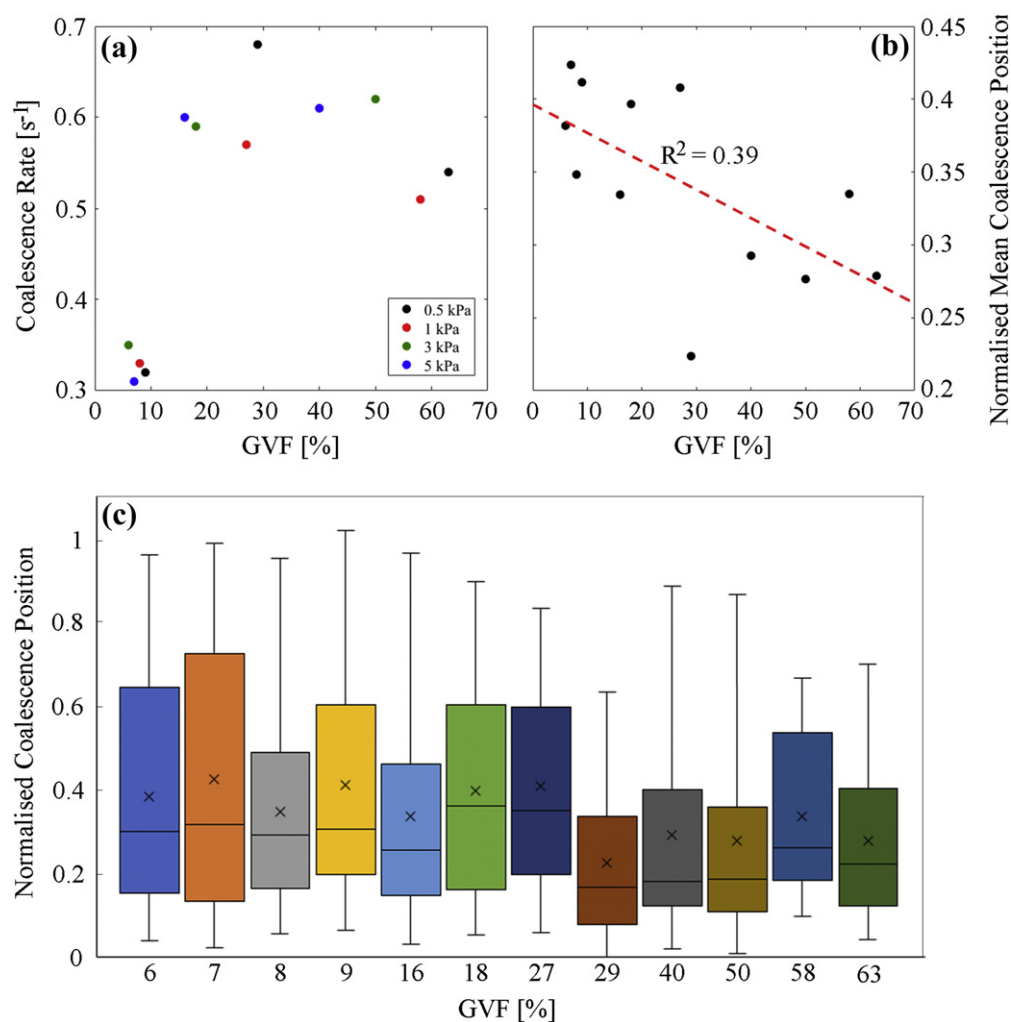


Fig. 4. Statistics and trends associated with coalescence during each experiment: (a) shows coalescence rate, i.e., coalescence events per second vs. gas volume fraction (GVF), with no clear discernible relationship between these parameters, other than lower coalescence rates for experiments with gas volume fraction < 10%; (b) shows the mean coalescence position, normalised by location in the liquid column (i.e., 1 is the fluid surface) vs. gas volume fraction, showing a general trend for lower coalescence locations with higher gas volume fraction; (c) shows box and whisker plots highlighting the interquartile range, median, and range of coalescence positions, with crosses within the boxes indicating the mean coalescence position.

linear manner vs. gas volume fraction values ranging ≈ 30 –65%. In this report, the slug base speed never exceeded twice the theoretical value from Viana et al. (2003) for single slug flow. In comparison, Krishna et

al. (1999) have shown that swarms of cap bubbles are capable of rising at six times the theoretical individual bubble value. Future work could explore the potential for using such laboratory derived relationships,

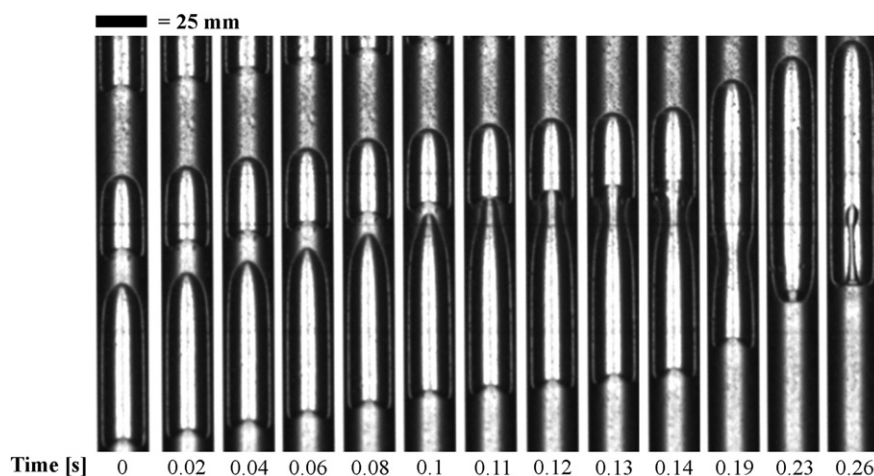


Fig. 5. A time-series through the coalescence process, showing the key stages, i.e., deformation and elongation of the trailing slug nose through to capture. This coalescence event is taken from the Lab 3 experiment with gas volume fraction of 58%.

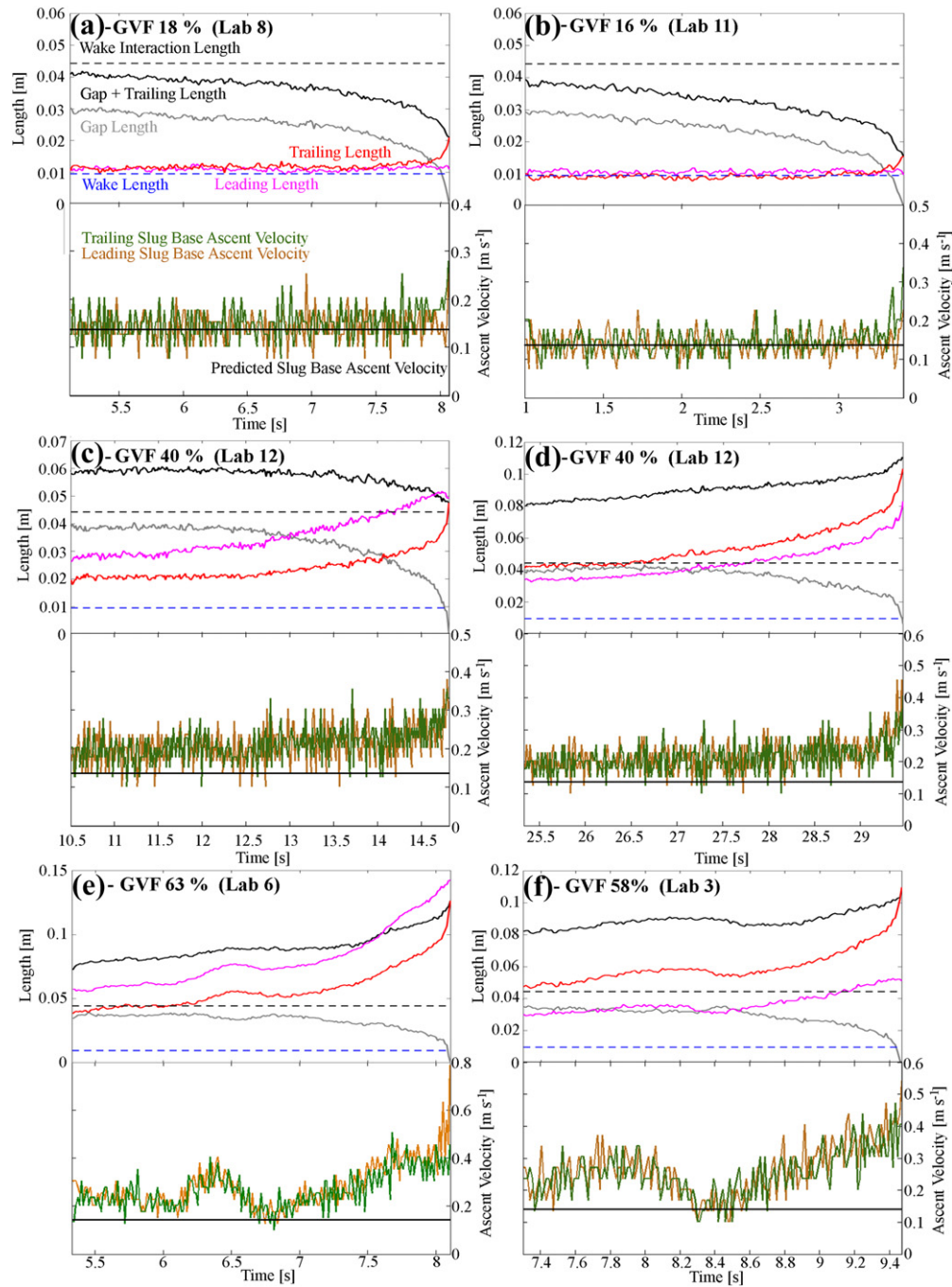


Fig. 6. Example time series data of coalescence events from the laboratory experiments showing slug lengths, inter-slug spacings, slug base rise speeds, wake (≈ 0.12 m) and wake interaction lengths (≈ 0.5 m) and the theoretical slug base rise ascent velocity (≈ 0.14 m s⁻¹) for a single slug scenario (Viana et al., 2003). In a) and b) coalescence occurs as expected for slugs following single slug behaviour. In c) coalescence occurs in a similar manner but with higher average slug base ascent velocities. In d), e) and f) there is a marked departure from single slug behaviour, with coalescence driven by vertical expansion of the trailing slug, as evidenced by an increasing gap plus trailing length prior to merging of the slugs. See main text for further detail.

in parallel with gas volume fraction values from field measurements of gas mass release, to determine slug lengths and rise speeds within the conduit, and to perform this analysis through time, potentially tracking trends in activity associated with changing eruptive magnitude or frequency.

The observations made in this study suggest that transport times of gas from depth which drive slug-driven strombolian volcanism could be lower than expected, meanwhile, expansion-driven interaction within slug trains could facilitate the growth of far larger explosive slugs (e.g., Llewellyn et al., 2014). A key parameter of use here, particularly where gas measurement could be difficult, would be the amount of gas

overpressure associated with bursting gas slugs (e.g., Vergnolle and Brandeis, 1996; Vergnolle et al., 2004; Vergnolle and Ripepe, 2008; Gerst et al., 2013). Gas overpressure could be used to estimate burst frequency and slug lengths, which could then be used to determine the significance or presence of expansion driven slug coalescence.

Future work could focus on furthering our understanding of the drivers and fluid dynamics of strombolian volcanism, by considering the role of slug interaction and coalescence, as reported here, alongside other models aimed at characterising statistics of slug release from depth, e.g., from collection and release of gas at conduit heterogeneities or collapsing foams (Jaupart and Vergnolle, 1988). The research

Table 2

Mean rise speeds (in m s^{-1}) of the bases of the leading (Slug 1) and trailing (Slug 2) slugs, during a number of coalescence events between slug pairs. These speeds were calculated prior to coalescence, during coalescence (i.e., in the <1 s window immediately prior to the moment of capture) and over the whole rise sequence. The italicised rows refer to coalescence events where the leading slug base travels faster than that of the trailing slug i.e., where coalescence is purely driven by vertical expansion of the trailing slug nose. The *Slug 1 data refer to approximate liquid velocities, from Eq. (6), for the fluid above the leading slug using a C value of 0.2. GVF is gas volume fraction.

GVF (%)	Pre coalescence		During coalescence		Whole sequence		Liquid	Experiment
	Slug 1	Slug 2	Slug 1	Slug 2	Slug 1	Slug 2	*Slug 1	
6	0.12	0.13	0.13	0.15	0.12	0.13	Stagnant	Lab 7
8	0.12	0.13	0.13	0.17	0.12	0.14	Stagnant	Lab 1
9	<i>0.13</i>	<i>0.13</i>	<i>0.17</i>	<i>0.15</i>	<i>0.15</i>	<i>0.14</i>	<i>Stagnant</i>	<i>Lab 4</i>
16	0.14	0.14	0.14	0.15	0.14	0.15	Stagnant	Lab 11
16	0.14	0.14	0.15	0.15	0.14	0.15	Stagnant	Lab 11
18	0.14	0.14	0.14	0.15	0.14	0.15	Stagnant	Lab 8
27	0.16	0.16	0.2	0.23	0.18	0.2	0.02	Lab 2
29	0.14	0.15	0.14	0.21	0.14	0.18	Stagnant	Lab 5
29	0.14	0.15	0.15	0.17	0.14	0.16	Stagnant	Lab 5
29	0.14	0.14	0.15	0.16	0.15	0.15	Stagnant	Lab 5
40	0.2	0.2	0.23	0.24	0.21	0.21	0.03	Lab 12
40	0.18	0.2	0.2	0.21	0.19	0.21	0.02	Lab 12
40	0.2	0.2	0.24	0.24	0.22	0.22	0.04	Lab 12
40	<i>0.2</i>	<i>0.19</i>	<i>0.23</i>	<i>0.22</i>	<i>0.22</i>	<i>0.21</i>	<i>0.04</i>	<i>Lab 12</i>
50	0.21	0.22	0.23	0.24	0.22	0.22	0.04	Lab 9
50	0.22	0.22	0.24	0.23	0.23	0.22	0.04	Lab 9
50	0.21	0.21	0.24	0.24	0.22	0.22	0.04	Lab 9
50	0.22	0.21	0.26	0.23	0.24	0.22	0.05	Lab 9
50	0.21	0.2	0.23	0.23	0.23	0.22	0.04	Lab 9
50	0.21	0.21	0.22	0.24	0.21	0.22	0.03	Lab 9
58	0.25	0.24	0.33	0.31	0.28	0.27	0.07	Lab 3
58	0.23	0.22	0.31	0.27	0.26	0.24	0.06	Lab 3
58	0.25	0.24	0.27	0.26	0.26	0.25	0.06	Lab 3
63	0.23	0.22	0.43	0.36	0.36	0.31	0.11	Lab 6
63	0.24	0.23	0.37	0.33	0.28	0.26	0.07	Lab 6
63	0.24	0.24	0.22	0.22	0.23	0.23	0.04	Lab 6
63	0.25	0.24	0.27	0.27	0.26	0.26	0.06	Lab 6
63	0.23	0.23	0.28	0.28	0.25	0.25	0.05	Lab 6

reported here could also form part of a wider framework, focused on improving understanding of how and why volcanoes transition between different forms of basaltic degassing (i.e., passive, puffing, strombolian, and Hawaiian), given the intrinsic link between these scenarios and the interaction and mass of ascending bubbles of various morphologies. A clearer understanding of these transitions, building upon earlier works on this theme (e.g. Parfitt and Wilson, 1995), could be important for better understanding the evolution of eruptive episodes.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jvolgeores.2017.10.009>.

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Appendix A

We provide the raw data used to calculate average slug base ascent velocity, which were used for Fig. 3a, in Supplementary Table 1. Here, the slug base ascent velocity was calculated for non-coalescing slugs, as including, data for coalescing slugs would skew data to higher velocities. We also provide all the raw data needed to produce Fig. 3c, including

burst lengths and repose times in Supplementary Table 2. Supplementary Video 1 contains the slow motion video of all the experiments.

Appendix B

In Fig. 6 we present coalescence tracks which encapsulate the main observed behaviours during coalescence events. Figs. S1 and S2 present the remaining coalescence tracks, where Fig. S1 highlights behaviour associated with a single slug flow regime (i.e., Fig. 6a and b), and Fig. S2 highlights behaviour departing from the characteristics of a single slug flow regime (i.e., Fig. 6c, d, e, and f).

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